REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS

AD-A219 834

3. DISTRIBUTION / AVAILABILITY OF REPORT

Approved for public release; distribution is unlimited

5. MONITORING ORGANIZATION REPORT NUMBER(S)

AFOSR.TR. 90-0552

6a. NAME OF PERFORMING ORGANIZATION Penn State University	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NA
6c. ADDRESS (City, State, and ZIP Code) Mechanical Engineering Bldg. University Park, PA 16802		7b. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling AFB, D.C. 20332-6448
8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR/NA	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-87-0097
8c. ADDRESS (City, State, and ZIP Code) Building 410 Bolling AFB, D.C. 20332-6448		10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT. NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2308	A2	

11. TITLE (Include Security Classification)

Premixed Turbulent Flame Propagation

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 86/11/1 TO 89/10/3	14. DATE OF REPORT (Year, Month, Day) 90/2/12	15. PAGE COUNT 15

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Premixed Turbulent Combustion; Turbulent-Flame Interactions;
			Turbulent Flame Propagation; Turbulent Flame Structure

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The results of an experimental study of turbulence-flame interactions and their effect on turbulent flame propagation are reported. Experiments are conducted in a new turbulent flow system which is capable of producing relative turbulence intensities as high as 100 percent. Using a freely propagating, one-dimensional flame configuration, measurements are made using LDV of the mean velocity, turbulence intensity, integral time scale, energy spectrum, Reynolds stress, and integral length scale, at a fixed location both before and after flame arrival. A complete set of such measurements has been made at one operating condition which characterize both the magnitude of flame generated turbulence and its anisotropic nature. The freely propagating, one-dimensional flame configuration has also been used to study the effect of turbulence on turbulent flame structure. Two-dimensional Mie scattering is used to obtain a two-dimensional slice of the turbulent flame surface. Such measurements have been made at 15 different conditions over a very broad range of turbulence Reynolds and Damkohler numbers and have been analyzed to determine the fractal nature of the turbulent flame surface. The results of these measurements show that premixed turbulent flame surfaces are fractal throughout the reaction sheet regime and that the fractal dimension increases with

key words:

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☑ SAME AS RPT. ☑ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Julian M. Tishkoff	22b. TELEPHONE (Include Area Code) (202) 767-4935	22c. OFFICE SYMBOL AFOSR/NA

DD Form 1473, JUN 86

Previous editions are obsolete.

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RESEARCH OBJECTIVES

The objective of this research is to develop an improved understanding of flame-turbulence interactions and their effect on flame propagation, flame structure and flame-generated turbulence. More specifically, experiments are performed which are intended to provide an improved phenomenological description of the interaction between the turbulent flow field and the turbulent flame structure and of the role that this interaction plays in determining the flame's mass burning rate. Such information will be used in the formulation and validation of phenomenologically correct turbulent combustion models.

APPROACH

Experiments are conducted using a new flame configuration which is based on a freely-propagating premixed turbulent flame. This flame configuration has a number of important advantages over flames which have been used by other researchers, such as rod stabilized and conical turbulent flames. These advantages include the absence of flame stabilization effects, the absence of mean shear, and the ability to operate over a broad range of turbulence Reynolds and Damkohler numbers, including values which are typical of those encountered in most practical combustion systems. Turbulent flows are produced by a novel turbulence generator which is capable of producing relative turbulence intensities as large as 100 percent, while maintaining mean velocity and turbulence intensity profiles which are uniform to within ± 10 percent over the entire cross-section of the test section. Three versions of this turbulent flow reactor have been constructed. One operates at pressures down to 0.2 atmospheres, a second operates at atmospheric pressure, and a third operates at pressures up to 20 atmospheres. These systems are used to study the growth of spark ignited, spherical, turbulent flames and propagating "one-dimensional" turbulent flames.

In order to characterize turbulence-flame interactions and their effect on flame-generated turbulence, flame structure and flame propagation, the following measurements are made:

i) Laser Doppler velocimetry is used to characterize the turbulent flow and to thereby characterize the effect of the flame on the turbulence. These measurements are made at a fixed point as a function of time both before and after flame arrival. Such measurements are ensemble averaged over as many as 2000 individual flame events to obtain a statistical description of the turbulent flow. The turbulence parameters which are measured include mean velocity, turbulence intensity, integral time scale, energy spectrum, integral length scale, and Reynolds stress. Velocity components both parallel and normal to the mean flame front are measured and the integral length scale is determined directly from a two-point spatial correlation.

ii) Two-dimensional Mie scattering is used to characterize the boundary between the unburned and burned gases, i.e. the turbulent flame structure. These measurements are made using a pulsed, frequency doubled Nd:YAG laser which is focused into a 300 micron thick sheet and is synchronized with the flame's passage. Light scattered by micron-sized zirconium oxide particles, which are added to the flow, is detected by a 128x128 diode array camera. The recorded images, from a nominal 3 cm x 3 cm field of view, are stored using a personal computer based frame grabber. The stored images are processed into a two color, i.e. unburned and burned gas, format which thereby defines a two-dimensional "slice" of the turbulent flame surface. The two-dimensional flame boundary is then analyzed to determine the fractal nature, i.e. the fractal dimension and the inner and outer cut-offs, of the turbulent flame surface.

iii)   A spherical flame geometry was choosen for measuring the flame propagation rate because it is least susceptible to large scale effects on the overall flame area, and therefore provides an unambiguous measurement of the turbulent to laminar flame speed ratio. High speed laser shadowgraphy is used to measure the growth rate of the spark ignited, turbulent spherical flames. The shadowgraph images are recorded at 4000 frames per second on a Spin-Physics video camera system. The flame boundary shown in each shadowgraph image is then digitized, from which an equivalent flame kernel radius is calculated. Results are then plotted in terms of the equivalent flame kernel radius versus time following ignition. During and shortly after ignition, the growth rate of the spherical flame provides valuable information regarding the effects of the ignition system characteristics and the transition from an initial laminar growth rate to a fully developed turbulent growth rate. At long times after ignition the measured growth rate of the spherical flame, $\dot{R}$, is related to the turbulent flame speed, S_T, by the following simple relationship:

$$\dot{R} = \frac{\rho_u}{\rho_b} S_T , \qquad\qquad [1]$$

where ρ_u and ρ_b are the unburned and burned gas densities, respectively.

RESEARCH ACCOMPLISHMENTS

Flame-Generated Turbulence

To date, an extensive characterization of flame-generated turbulence has been made at one operating condition in the freely-propagating flame configuration which was developed for this study of turbulence-flame interactions. The particular case studied was an unconfined, premixed propane-air flame at an equivalence ratio of 1.0 with an upstream turbulence intensity of 25 cm/sec and integral length scale of 8mm. The following observations can be made from these measurements:

i) The normal turbulence intensity increases slightly ahead of the flame and by a factor of five to six across the flame, while the parallel component is relatively constant ahead of the flame and increases by only two to three times across the flame.

ii) The density weighted kinetic energy doubles across the flame. This increase begins well ahead of flame arrival.

iii) The normal, transverse integral length scale increases 100% across the flame, while the parallel component increases by only 50%.

iv) The degree of autocorrelation of both u' and v' increases across the flame, resulting in an increased turbulence time scale behind the flame. The oscillating character of the normal velocity component autocorrelation behind the flame suggests the presence of large scale turbulent motion.

v) For the normal velocity component, there is an increase in high frequency fluctuations ahead of the flame and a shift in turbulence energy towards lower frequencies behind the flame. In contrast, the spectral distribution of the parallel velocity component is relatively unchanged through the flame.

These results clearly show that successful modelling of turbulent reacting flows must account not only for the production of turbulence, but also for the anisotropic nature of the turbulence as well. At this point, it is generally unknown what dependence these results have on the characteristics of the incident turbulence and on the amount of heat release. On-going experiments, described later in this report, are extending these measurements to a range of conditions in order to address this question.

Turbulent Flame Structure

The structure of freely propagating, premixed turbulent flames has been studied over a range of turbulence Reynolds numbers from 52 to 1431 and Damkohler numbers from 10 to 889. This encompasses a significant portion of the reaction sheet regime of turbulent combustion. Using a fractal analysis, the fractal dimension, inner cutoff and outer cutoff of the two-dimensional flame structure measurements have been examined.

The flame surface measurements exhibit fractal behavior over this entire range of conditions, where the fractal dimension increases with the turbulence intensity to laminar flame speed ratio (u'/S_L) from a value of 2.13 at $u'/S_L = 0.24$ to a value of 2.32 at $u'/S_L = 11.9$. These results support the argument that the upper limit to the flame surface fractal dimension is that of passive scalar surfaces, i.e. 2.35. That the lower limit does not appear to be approaching a value of 2.0 is attributed to the effect of hydrodynamic instabilities.

The inner cutoff was not observed due to experimental limitations, however, several theoretical expressions were examined in comparison with the measurements. The Gibson scale and an expression for the inner cutoff proposed by Gouldin are both found to over predict the inner cutoff at low values of u'/S_L.

The outer cutoff was found to occur at scales comparable to the integral scale of turbulence, however, it is not a sharp cutoff but a gradual transition from fractal behavior.

A heuristic relationship was formulated which predicts the observed change in the flame surface fractal dimension as a function of the turbulence intensity to laminar flame speed ratio. It is assumed that at high turbulence intensities, the effect of turbulent convection dominates, distorting the flame surface as if it were a passive scalar surface. In the limit of very high turbulence intensities, the surface fractal dimension approaches a limiting value, D_T, which corresponds to the fractal dimension of passive scalar surfaces. While at low turbulence intensities, the process of flame propagation dominates, smoothing the flame surface. In the limit of very low turbulence intensities, the flame surface fractal dimension approaches a limiting value, D_L, which is defined as the laminar limit. At intermediate turbulence intensities, the flame structure is determined by the competition between these two processes which can be represented by the relationship,

$$D_F - D_L/(1+u'/S_L)+D_T/(1+S_L/u') . \qquad [2]$$

The flame surface fractal dimensions predicted by this heuristic relationship agree well with those obtained in this study and by other researchers in a variety of flame configurations.

Using the heuristic fractal dimension relationship and the Kolmogorov and integral scales as inner and outer cutoffs, respectively, a fractal turbulent flame speed model is obtained which depends on the turbulence intensity, integral length scale and laminar flame speed. Meaningful comparisons with other turbulent flame speed models, however, are not possible since they typically depend only on u'/S_L. This fractal dimension relationship has also been used to develop a model of turbulent spherical flame growth, which is described in the next section.

Turbulent Spherical Flame Model

The effect of turbulence on spark ignited flame kernel growth is a problem of considerable practal importance, since it is typically the flame kernel growth rate which determines the ignition

limits of actual combustion systems. In the absence of additional ignition energy following gas breakdown, the growth rate, $\dot{R}$, of a spherical flame kernel is related to the flame speed by the following expression:

$$\dot{R} - \frac{\rho_u}{\rho_b} S ,$$ [3]

where ρ_u and ρ_b are the unburned and burned gas densities, respectively, and S is the laminar or turbulent flame speed. This expression accounts for both flame propagation and thermal expansion due to the flame's chemical heat release. The effect of turbulence on the growth of spherical flames as expressed by this equation is through changes in the flame speed. The fundamental effects of turbulence on flame speed are much the same in a transient spherical flame as in a fully developed flame, where turbulence scales which are larger than the laminar flame thickness act to convectively distort or wrinkle the flame surface. This increases the flame's surface area and as a result the overall mass burning rate. On the other hand, turbulence scales which are smaller than the laminar flame thickness effectively increase the transport rates within the flame front and thereby increase the local burning rate. The local burning rate can also be effected by turbulent flame stretch, where sufficiently intense turbulence can actually result in local extinction of the flame. To date, the model developed in this work only accounts for the first of these effects, that is the enhancement of the flame speed due to the increased flame area.

The main difference between a fully developed turbulent flame and a turbulent spherical flame is that the spherical flame imposes its own characteristic time and length scales, i.e. its lifetime and diameter. To properly account for these imposed scales, it is necessary to allow for the fact that the turbulent flow consists of a range of turbulence time and length scales and that therefore the effect of turbulence actually increases with time until the spherical flame's characteristic time and length scales exceed the largest turbulence scales.

One approach which has been used to account for the range of turbulence time scales which affect the growth of a spherical flame is based on the turbulence energy spectrum. In this case, the effective turbulence intensity at a particular time, u'(t), is defined by the square root of the area under the energy spectrum over the range of frequencies which are greater than the reciprocal lifetime, i.e.,

$$u'(t)^2 - {}_{1/t}\!\int^{\infty} E(f)\ df.$$ [4]

It is also necessary, however, to account for the range of turbulence length scales which affect the growth of a spherical flame. To do so, a fractal description of the flame's surface is used. This description is based on the a heuristic relationship for the fractal dimension of turbulent flame surfaces which was developed in this study, i.e.,

$$D_F(t) = D_L/(1+u'(t)/S_L)+D_T/(1+S_L/u'(t)) , \qquad [5]$$

where in the case of a spherical flame the laminar limit, D_L, is 2.0 and the high Reynolds number limit, D_T, is choosen to be 2.35 based on measurements of the fractal dimensions of clouds in atmospheric turbulence. Note that the effective turbulence intensity, $u'(t)$, is used, therefore the fractal dimension of the spherical flame's surface is also a function of time.

Assuming that the turbulent to laminar flame speed ratio is simply equal to the turbulent to laminar flame area ratio, then for a fractal flame surface this can be expressed in terms of the fractal dimension and the so-called inner and outer cutoffs, ϵ_i and ϵ_o, i.e.,

$$S_t(t) /S_L = \frac{A_t}{A_L}(t) = \left[\frac{\varepsilon_i}{\varepsilon_o}\right]^{2-D(t)} , \qquad [6]$$

where the ratio of the turbulent to laminar flame area, and therefore the turbulent flame speed, is a function of time.

Based on the flame structure measurements previously discussed, the Kolmogorov (η) and integral (L) scales of turbulence where choosen as the inner and outer cutoffs in the turbulent spherical flame model, although it is clear that this is a subject which requires further study. To account for the fact that the initial size, i.e. following gas breakdown, of a spark ignited flame kernel is typically smaller than the integral scale, the above expression must be modified as follows:

$$S_T(t) = S_L\left[\frac{\eta}{R(t)/2}\right]^{2-D(t)} \qquad R(t){\leq}2L$$

$$[7]$$

$$S_T(t) = S_L\left[\frac{\eta}{L}\right]^{2-D(t)} \qquad R(t){\geq}2L$$

where it is assumed that a spherical flame can not accommodate wrinkles which are larger than half the flame's radius.

Equations [3], [4], [5] and [7] form the basis of the turbulent spherical flame model and can be used to predict the growth of such flames. The predictions of the fractal model of turbulent spherical flame growth have been compared with a number of different measurements made both in turbulent wind tunnels and spark ignition engines. These comparisons, although preliminary due to the limited amount of data on turbulent spherical flame growth which is available, are very encouraging in that they show reasonably good agreement over a broad range of turbulence conditions. One concern with the fractal model is that it requires extensive information regarding the turbulence properties, however a sensitivity study has shown that it is most sensitive to typical uncertainties in the values of the inner cutoff, the outer cutoff and the laminar flame speed.

High Altitude Relight

As an extension of this study, a specially designed version of the turbulent flow reactor was constructed which is capable of operating at pressures and temperatures down to 0.2 atmospheres and 260K, respectively. This particular aspect of the research was co-funded by Garrett Turbine Division of Allied Signal Corporation and was directed toward the study of ignition in gas turbine combustors under high altitude relight simulated conditions. The results of this study are intended to provide Garrett with previously unavailable information regarding the performance of their ignitors under high altitude relight conditions and in turn new insights regarding the ignition limit charcteristics of their combustors. The flame kernel growth rate measurements made with the Garrett ignitor, as well as those made in a parallel Department of Energy funded study of ignition under automotive type conditions, provide data which is necessary to validate the fractal model of turbulent spherical flames discussed in the previous section. This model, when extended to include the effects of spark assisted growth, will be used in collaboration with Garrett engines to develop new ignition limit correlations and as an ignition submodel in Garrett's multidimensional combustor codes.

The parameters which are varied in these tests include pressure, temperature, equivalence ratio, turbulence intensity, mean velocity, degree of mixing, and oxygen enrichment. Measurements are made at ea_h operating condition of the ignition limits and the flame kernel growth rate. To date a total of 40 operating conditions have been studied, all at 1 atmosphere, 300K conditions.

ON-GOING RESEARCH

Additional experiments are underway but have not been completed at the time that this report was written. These experiments are described below. The results from this work will be published in at least two papers which are expected to be submitted to Combustion Science and Technology by September of this year.

Flame-Generated Turbulence

While there are many fundamental mechanisms which contribute to turbulence-flame interactions, the two most important experimental parameters are likely to be the turbulence intensity to laminar flame speed ratio and the heat release rate. In order to independently evaluate the effect of these two parameters, experiments are in progress at the five different operating conditions listed below:

Case	u'	ϕ	Heat Release Parameter	u'/S_L
1	0.5	1.0	6.5	1.2
2	1.0	1.0	6.5	2.4
3	1.5	1.0	6.5	3.6
4	0.84	0.70	5.3	2.4
5	0.93	0.84	6.0	2.4

Note that cases 1, 2 and 3 are at constant heat release, while cases 2, 4 and 5 are at constant u'/S_L. These conditions go well beyond the conditions which have been reported in the literature, as does the extent to which the turbulence properties are characterized. As such, these measurements will provide extremely valuable new information regarding turbulence-flame interactions.

Flame Structure

The flame structure measurements that we have reported to date show that premixed turbulent flame surfaces are fractal over a broad range of turbulence Reynolds and Damkohler numbers and that the fractal dimension of the flame surface is related to the turbulence intensity to laminar flame speed ratio by the heuristic relationship we have proposed. Experiments are currently in progress in order to address the following important but unresolved questions regarding the fractal nature of premixed turbulent flame surfaces:

i) Although the Gibson scale would seem to be an appropriate choice for the inner cutoff, this is not supported by our measurements. Additional measurements are in progress with improved spatial resolution which is intended to reveal the inner cutoff in our fractal analysis.

ii) The effect of turbulent flame stretch on the flame's structure is not accounted for in the heuristic relationship for the flame surface fractal dimension or the turbulent spherical flame growth model. Obviously such effects are important, particularly in relationship to the

ignition limits and flame-out limits of gas turbine combustors. The experiments which are in progress involve a comparison between flames which are near the fuel lean limit, at an equivalence ratio of one, and near the fuel rich limit, but which have the same u'/S_L in all three cases. The Lewis number is also varied in these tests, which allows for the effects of preferential diffusion to be studied.

iii) In relating the fractal dimension of the two-dimensional flame structure measurements to that of the three-dimensional flame surface the fractal nature of the surface has been assumed to be isotropic. Since this important assumption is not necessarily true, experiments have been initiated where two-dimensional flame structure measurements are being made in three orthogonal planes, simultaneously.

Turbulent Spherical Flame Model

There are three major limitations of the turbulent spherical flame growth model in its current form. One of these is that the model does not account for the effects of the ignition system characteristics on both the initial size and initial growth rate of the spherical flame. The second is that the model does not account for the effects of flame stretch and the third is that the correct value of the inner cutoff is not known. All three of these subjects are areas of continuing research.

High Altitude Relight

The high altitude relight tests are continuing with support from Garrett. Particular emphasis is being placed on tests at low pressure (down to 0.3 atmospheres) and low temperature (down to 260K) conditions. Plans are also being made to extend this study to include ignition in well defined, partially vaporized sprays.

PUBLICATIONS

Videto, B.D. and Santavicca, D.A., "Premixed Turbulent Flame Propagation in a Pulsed Flame Flow Reactor," presented at the Eastern States Section of the Combustion Institute Fall Meeting, December 1986.

North, G. L. and Santavicca, D. A., "Fractal Analysis of Premixed Turbulent Flame Structure," presented at the Eastern States Section of the Combustion Institute Fall Meeting, December 1986.

Videto, B. D. and Santavicca, D. A., "Turbulence-Flame Interactions in an Unconfined, Premixed Turbulent Flame," presented at the Eastern States Section of the Combustion Institute Fall Meeting, November 1987.

North, G. L. and Santavicca, D. A., "Fractal Analysis of Turbulence-Flame Interactions," presented at the Eastern States Section of the Combustion Institute Fall Meeting, December 1988.

Santavicca, D. A., "Turbulence Effects on Ignition Flame Kernel Growth", Invited Paper presented at the Eastern States Section of the Combustion Institute Fall Meeting, December 1988.

Santavicca, D. A., Liou, D. and North, G. L., "A Fractal Model of Turbulent Flame Kernel Growth," SAE Paper No. 900024, February 1990.

Videto, B. D. and Santavicca, D. A., "Flame-Turbulence Interactions in a Freely-Propagating, Premixed Flame," accepted for publication in Combustion Science and Technology, 1990.

North, G. L. and Santavicca, D. A., "The Fractal Nature of Premixed Turbulent Flames," accepted for publication in Combustion Science and Technology, 1990.

PROFESSIONAL PERSONNEL

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C. A. Wilson (M.S. completed 9/88)

J. G. Zoeckler (M.S. completed 2/89; currently employed by NASA-Lewis)

INTERACTIONS

Results from this AFOSR funded study of premixed turbulent flame propagation were presented at the following meetings, workshops and seminars:

Department of Energy sponsored Dilute Homogeneous Charge Working Group Meeting, Apr. '86, Oct. '86, Apr. '87, Apr. '88, May '89 and Oct. '89.

General Motors Ignition Research Council Workshop, General Motors Research Laboratory, Mar. '87 and Dec. '87.

"A Fractal Model of Turbulent Flame Kernels." Seminar presented at Wright-Patterson AFB, Feb. '89.

Engineering Foundation Conference on Fluid Mechanics in IC Engines, Santa Barbara, CA, May '89.

Shell Workshop on Fuels and Combustion in IC Engines, Lake Vrynwy, Wales, Sept. '89.

Sandia Turbulence and Aerothermochemistry Working Group Meeting, Vanderbilt Univ., Nov. '89.

"The Role of Flame Structure in Premixed Turbulent Flame Propagation." Seminar presented at Imperial College, London, Sept. '89.

Extensive technical discussions have also been held at Garrett (Phoenix, AZ) on four separate occassions with Dr. John Sanborn (Supervisor, Combustion Science Engineering) and other Garrett Engineers regarding the high altitude relight research.